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Depth Release of Illusory Contour Shape in the Ehrenstein Grid

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In the Ehrenstein grid, bright illusory patches delineated by illusory contours are seen. In order to assess whether the illusory patches possess shape constancy, the Ehrenstein grid was viewed straight on and at various angles of slant with respect to the observer. Observers matched the apparent shape of the illusory patches with a circle or an ellipse defined by real lines in a reference stimulus. Results show that, when viewed at a slanted angle, the shape of the bright patches was deformed and became oval. Such deformation was much less when the illusory contours were replaced by real contours. We label this dissociation of shape perception from depth cues *depth release* to contrast it with the previously described phenomenon of *depth capture* in which depth cues displace the illusory patches in depth. As a common explanation for both effects, it is proposed that the illusory contours induced by line ends or line ends themselves provide only weak or ineffective depth signals.

Depth capture Depth release Illusory contours Ehrenstein grid Shape constancy

INTRODUCTION

In certain types of patterns, surface features can be perceptually displaced from their original position, e.g. by moving a superimposed textured screen over the surface (*motion capture*) (Ramachandran, 1987) or by holding a textured screen in front of the surface (*depth capture*) (Spillmann & Redies, 1981; Watanabe & Cavanagh, 1992). These phenomena can be induced in surfaces with both real and illusory contours and are of interest because they provide examples of specific interactions between mechanisms mediating different perceptual modalities. Generally, capture occurs under conditions in which the perceptual cues inducing the contours are overwhelmed by the cues signaling motion or depth.

We recently reported a phenomenon (Redies & Watanabe, 1993) that is different from depth capture but occurs under similar conditions. This phenomenon is induced in the Ehrenstein grid (Ehrenstein, 1941) where bright illusory patches are perceived as being circular in shape when viewed straight on. When viewed at a slanted angle with respect to the observer, however, the shape of the illusory patches appears to be deformed and becomes oval. This result suggests that the illusory patches posses little three-dimensional shape constancy. Unlike the illusory patches, the inducing grid itself is not subject to this deformation. We propose to call this phenomenon *depth release* to contrast it with depth (or stereo) capture (Ramachandran & Cavanagh, 1985; Watanabe & Cavanagh, 1992).

In the present study, we provide a quantitative examination of Redies and Watanabe's (1993) hypothesis concerning the deformation of the illusory patches in depth release and compare the phenomenon to the perception of the figures defined by real contours presented in the same inducing pattern. The existence of a possible common mechanism underlying both depth release and depth capture is suggested and discussed.

EXPERIMENT 1

Method

Observers. One male and three females ranging in age from 21 to 28 yr participated in this experiment. All of the observers were naive to the experimental conditions and the purpose of the experiment. The observers had normal or corrected-to-normal visual acuity (Snellen 20/20).

Stimuli. As shown in Fig. 1, four test stimuli were used. Figure 1 constitutes the Ehrenstein grid, which consists of a grid of two vertical and horizontal black lines. There were vertical and horizontal gaps in the four cross sections of the vertical and horizontal lines. In Fig. 1(a) the length of the gaps between the horizontal and vertical lines was the same (1 deg). In Fig. 1(b) the length of the gaps between the horizontal lines was also 1 deg, while the length of the gaps between the vertical lines was

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0.6 deg. In Fig. 1(c, d) circles and ellipses are drawn in, producing real contours connecting the inner ends of the vertical and horizontal lines that produced the gaps in Fig. 1(a, b) respectively. The length of the horizontal and vertical lines comprising the grids subtended 2 deg. The purpose for using the grids with ellipses as well as the grids with circles was to avoid the situation in which the observers might have noticed that only circles were presented.

One circle and seven ellipses with black contours were used as reference stimuli for matching the test stimuli. The length of the horizontal radius was 1 deg for all of the reference stimuli. The ratio of the horizontal to vertical radius was varied in nine steps, 1.00, 1.04, 1.11, 1.29, 1.43, 1.66, 2.00, 2.43, and 2.92. All the reference stimuli were presented in a row; the circle was on the leftmost position and the ellipses with higher horizontal to vertical radius ratio were presented in progressively right loci.

The width of the strokes of the vertical and horizontal lines of the Ehrenstein grid and of the contours of the circles and ellipses of the test and reference stimuli was the same (2.7 min arc). The luminance of the black lines and the circles and ellipses of the test and reference stimuli were all 0.5 cd/m^2 and the luminance of the white background was 33.0 cd/m^2.

Apparatus. Two boards were used that could be rotated along their horizontal midlines. Each of the four test figures was attached to the left board and the set of reference stimuli was attached to the right board. Each of the test and reference stimuli was attached to the center of each board. When the board was rotated the stimuli were also rotated about their horizontal midlines. The degrees of slant of the test stimuli were 0, 16, 26, 39, 46, 53, 60, or 66 deg. The degree of slant of the reference stimuli was either 0 or 46 deg. It was 0 deg when the stimuli were presented upright and 66 deg when the stimuli were slanted by 66 deg with the tops of the stimuli slanted away from the location of the observer. The boards to which the figures were attached were located 20 cm away from the front of a rectangular enclosure made of black cloth. The distance between the two boards and the observer was 100 cm. The test and reference stimuli were observed through 18 × 18 and 24 × 7 cm rectangular windows respectively. The windows were 7 cm apart and were at the same height as the observer's eye level. The size of the windows was

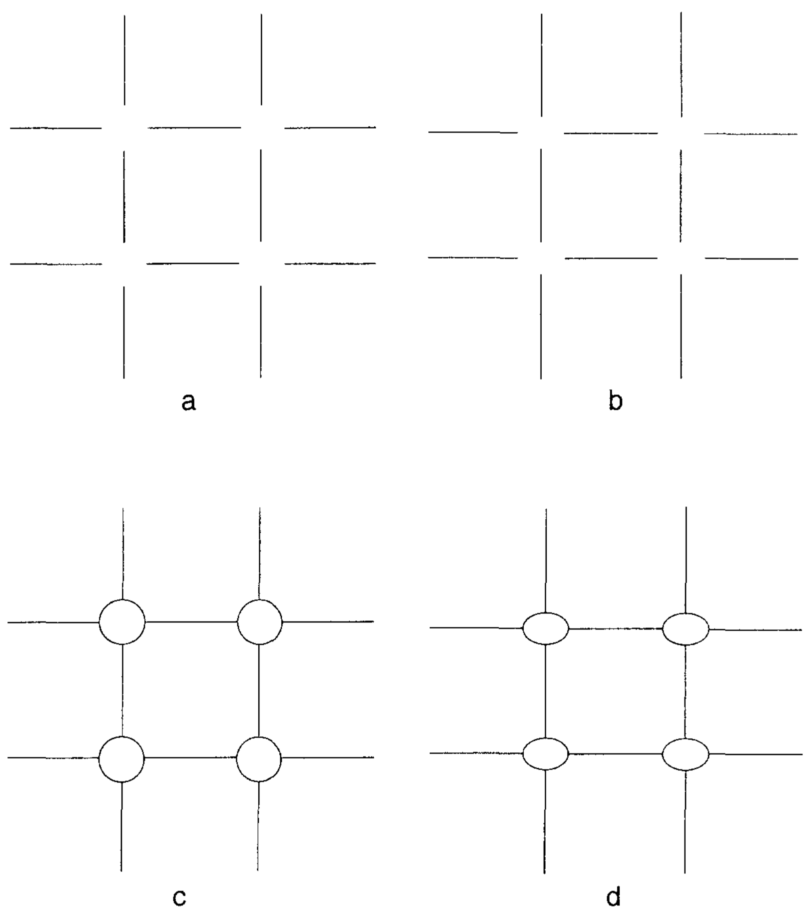

FIGURE 1. The test stimuli used for Expt 1. (a) The Ehrenstein grid where the horizontal and vertical lines of the grid have gaps of the same width in their intersections. When viewed straight on, a round illusory bright patch is observed connecting the inner ends of the lines of each gap. When the page is slanted from the vertical plane away from the observer, the illusory patches in the Ehrenstein grid become oval. (b) The grid where the ratio of the width of a horizontal to that of the vertical gap is 1.67. Circles (c) and ellipses (d) with black contours are drawn connecting the inner ends of lines of the Ehrenstein grids same as (a) and (b) respectively.

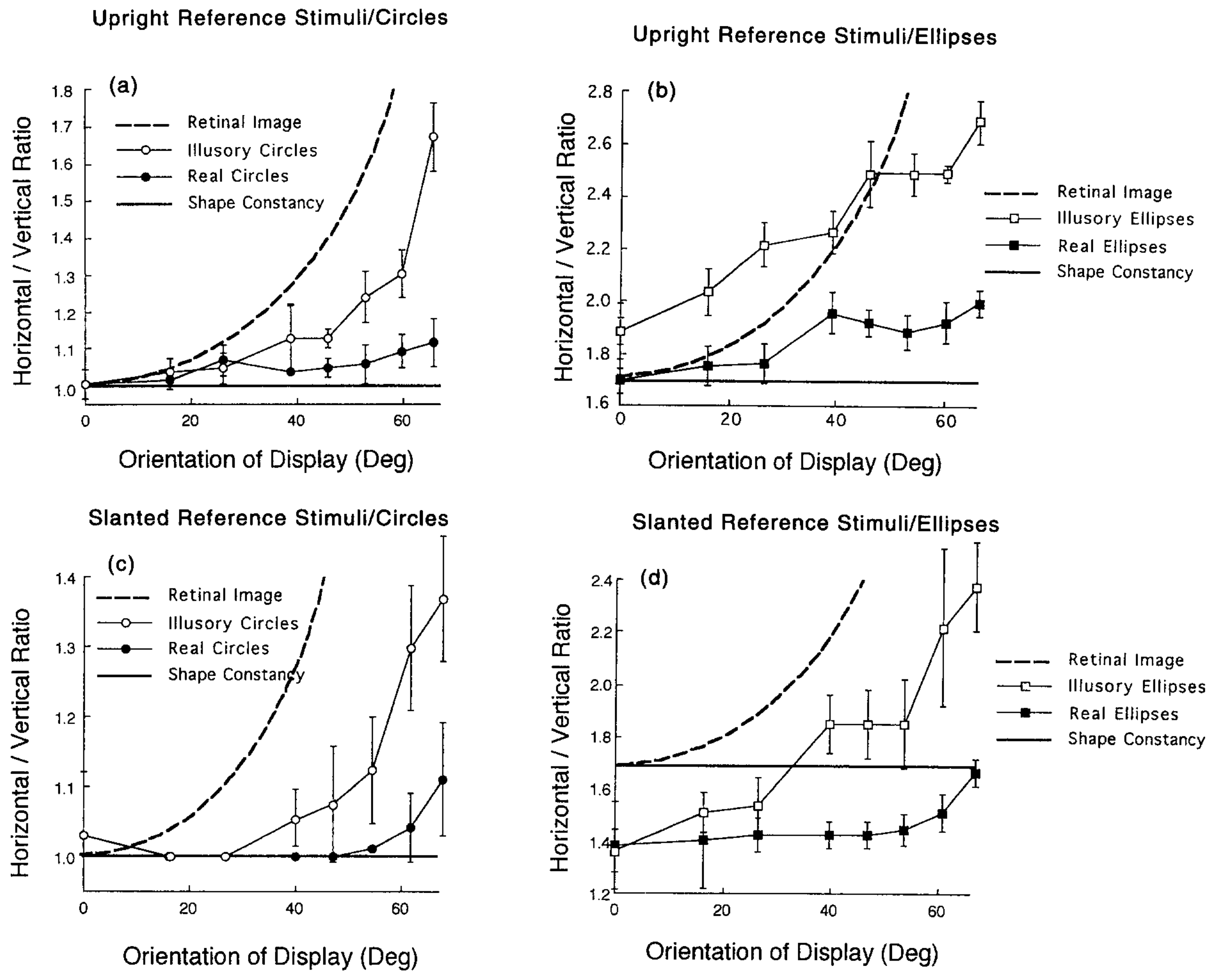

FIGURE 2. Results of Expt 1. The mean physical ratio of the horizontal to vertical radius of the ellipse (or the circle) of the reference figures the observers chose to match the shape of the presented test stimulus, plotted as a function of the degree of slant of the test stimulus. (a) and (b) show results for the upright reference stimuli, and (c) and (d) for the reference stimuli slanted by 46 deg. (a) and (c) show results for the illusory and real circles, and (b) and (d) for the illusory and real ellipses. The dashed line in each graph shows the physical horizontal/vertical ratio obtained if a perceived figure were perfectly dependent on the retinal shape and the bold line shows the horizontal/vertical ratio obtained if shape constancy were perfect.

sufficiently small so that only the test and reference figures were visible through each of the windows. The observers were seated in a chair located inside the enclosure. The height of the chair was adjusted between observers so that the center of the stimuli was at eye level to the observer. In order to avoid any horizontal distortion of the retinal image of each of the test and reference stimuli, the apparatus was designed so that the observers' line of sight became orthogonal to the horizontal axis of each of the stimuli when he or she turned toward the stimuli. Both test and reference stimuli were illuminated by a spotlight placed at the outer top of the enclosure.

Procedure. The gaps in the intersections of the grid in Fig. 1(a, b) formed illusory contours that were perceived as "connecting" the inner tips of the lines producing the gaps. In Fig. 1(c, d), the circles and ellipses were drawn in, connecting the inner tips of the lines. In each trial, the observers saw only one of the four test stimuli [Fig. 1(a, b, c, d)] at one of the eight degrees of slant. The observer's task was to select one of the reference stimuli presented on the right side to match the original shape (as seen when not slanted) of the illusory or real figures presented on the left side. The observers were further instructed to turn their heads rather than simply move their eyes when turning their gaze from the fixation point of one of the test or reference stimuli to another. There were two conditions in terms of degrees of slant of the reference stimulus. In the upright condition the reference stimulus was upright (0 deg). In the slanted condition the reference stimulus was rotated by 46 deg away from the observer. Within each reference angle condition each of the four test stimuli with the same degree of slant was presented 10 times. The order of the conditions and presentation of the four test stimuli and the eight different degrees of slant were pseudo-randomized within observers. Each observer viewed a total of 640 trials [4 test stimuli (circle vs ellipse and illusory vs real contours) $\times$ 2 degrees of slant of reference stimuli $\times$ 8 degrees of slant of test stimuli $\times$ 10 repetitions].

Results

Figure 2 shows the mean ratio of the horizontal to vertical radius of the reference figures chosen by observers to match the shape of the presented test stimulus as a function of the degree of slant of the test stimulus. Both with the reference stimuli upright [Fig. 2(a, b)] and at

46 deg of slant [Fig. 2(c, d)], several common results were observed. For the illusory circle and ellipse conditions the mean horizontal/vertical ratio of the ellipses matched by the observers became larger with increasing degrees of slant of the test stimuli. On the other hand, with the real circle and ellipse, this tendency was considerably less.

Discussion

The results of the present experiment (Fig. 2) show that the illusory figures in the Ehrenstein grid become more deformed with increasing degrees of slant of the test stimuli than the real circles and ellipses. They also suggest that the deformation of the illusory contours may be partially determined by the retinal image. One possible explanation is that there is a lack of shape constancy with illusory contours in the Ehrenstein grid. However this lack is not complete since the perceived deformation of the illusory contours is smaller than the deformation that would be expected if the retinal image were the sole determinant of the shape of illusory figures (dashed line in Fig. 2). In contrast, the figures defined by real contours are much more resistant to such deformation, i.e. shape constancy is relatively well preserved (Thouless, 1931; also see Sedgwick, 1986 for a review). These results provide a quantitative confirmation of Redies and Watanabe's (1993) hypothesis that the three-dimensional shape of the illusory figure in the Ehrenstein grid does not possess strong shape constancy.

In the current experiment a degree of slant of the test stimuli was not always the same as that of the reference stimuli. To control for the possibility that this discrepancy might somehow bias the data, we included only those data obtained when both the test stimuli and the reference stimuli were presented with the same degree of slant. Figure 3 shows the mean horizontal/vertical axis ratio for the illusory figures (circles and ellipses) divided by the mean horizontal/vertical axis ratio for the real contour figures (circles and ellipses) when both test and reference stimuli were upright and when both were slanted by 46 deg. For both circles and ellipses, the mean ratios were higher at 46 deg than upright. These results further confirm that illusory contour figures tend to appear more distorted than real contour figures when slanted.

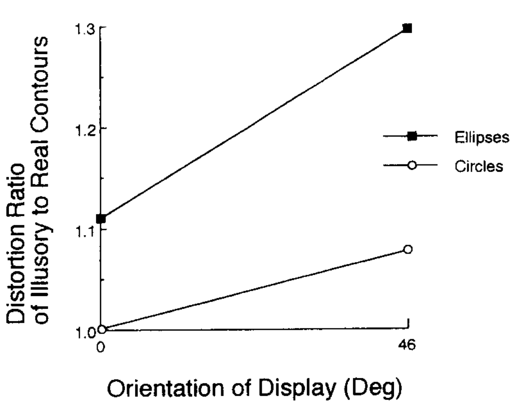

FIGURE 3. Results of Expt 1. The mean physical horizontal/vertical axis ratio of the matched reference stimuli for illusory figures (circles and ellipses) divided by the mean physical horizontal-to-vertical axis ratio for real contour figures (circles and ellipses) when both test and reference stimuli were upright and when they were both slanted by 46 deg. For both circles and ellipses the mean ratios were higher at 46 deg slanted than upright.

EXPERIMENT 2

The results of Expt 1 show that even real contour figures do not seem to possess perfect shape constancy (Fig. 2). With increased slant of the display including the test stimuli, the horizontal/vertical axis ratio of the matched reference figures became slightly larger for the real circles and ellipses. In addition, the ratio tends to be lower with the reference stimuli at 46 deg than with the reference stimuli upright, indicating that the reference stimuli themselves do not possess perfect shape constancy in the given condition. This may be because binocular disparity and linear perspective of the Ehrenstein grid were the only cues for slant in Expt 1. It is known that with fewer cues for slant, less shape constancy is obtained (Thouless, 1931). On the other hand there is a possibility that in Expt 1, the contours of the real circles and ellipses themselves might have been used as additional cues for slant, whereas these cues were not present in the case of the illusory circles and ellipses. If so, there should be more information about slant in the test stimuli with the real contour figures than in the test stimuli that induce the illusory figures. This insufficiency of depth cues or slant information in the illusory contour figures might have caused the illusory circles and ellipses to appear more deformed than the real circles and ellipses.

One way to examine this possibility is to add textures or other figures defined by real contours to the test stimuli so that there will be more depth cues in the test stimuli and, therefore, the slant of the test stimuli can be more precisely measured. If the illusory circles and ellipses are deformed with increasing degrees of the slant of the test stimuli even with these depth cues added while the real circles and ellipses show a stronger tendency for shape constancy, then we may say that the possibility is ruled out that the deformation of the illusory figures occurred because of insufficient cues for depth and slant with the test stimuli that induced the illusory figures in Expt 1.

Method

Observers. Two males and one female ranging in age from 21 to 22 yr participated in this experiment. None of the observers participated in Expt 1. They were all naive to the experimental conditions and the purpose of the experiment. The observers had normal or corrected-to-normal visual acuity (Snellen 20/20).

Stimuli. As shown in Fig. 4 (a, b, c, d), Xs and a square frame were added to each of Fig. 1 (a, b, c, d) so that the test stimuli would have stronger depth cues. The Xs were placed sufficiently far from the illusory contours so as not to have any bias on the shapes of the illusory contour figures. The square frame connected the outer tips of the lines of the Ehrenstein grid.

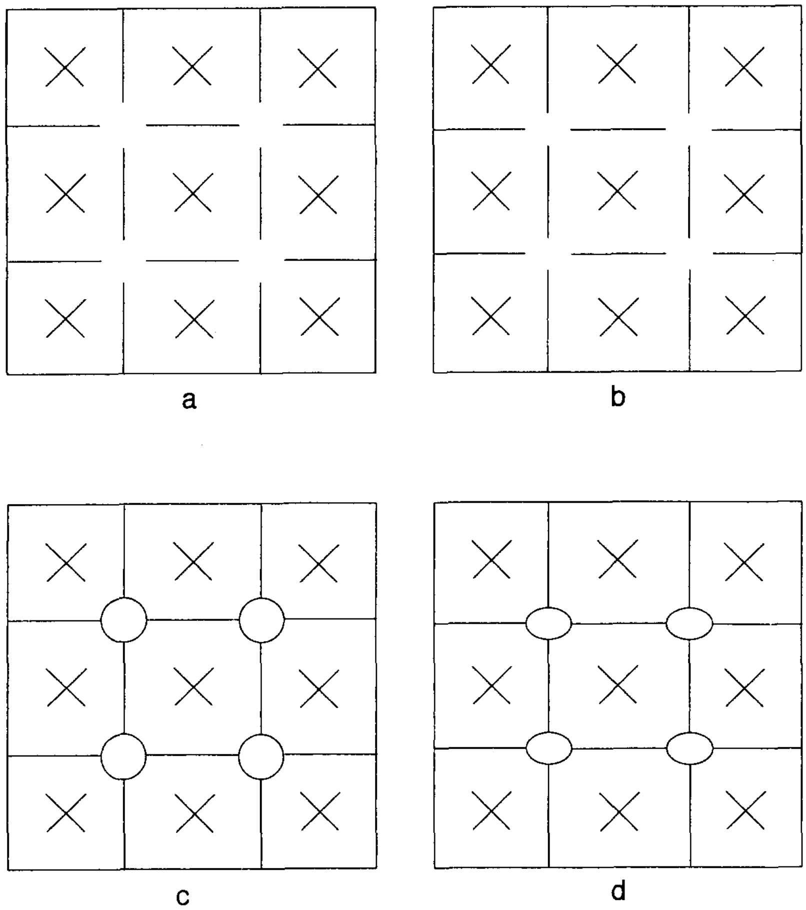

FIGURE 4. The test stimuli used in Expt 2. In (a), (b), (c) and (d), Xs and a square frame are added to (a), (b), (c) and (d) of Fig. 1, respectively.

Procedure. The experimental procedure was identical to that of the upright condition of Expt 1 in which the reference stimulus was constantly upright (0 deg).

Results and discussion

As shown in Fig. 5, for the illusory circle and ellipse conditions, basically the same results were obtained as in Expt 1. That is, the mean horizontal/vertical axis ratio of the ellipses matched by the observers became larger with increasing degrees of slant of the test stimuli. In contrast, a stronger tendency of shape constancy of the real circles and ellipses was obtained in Expt 2 as compared with Expt 1.

This stronger tendency of shape constancy toward the real figures in Expt 2 suggests that with the Xs and the square frame added, slant of the display was measured more precisely in Expt 2 than without them in Expt 1. This further suggests that the Xs and the square frame were strong cues for depth and slant of the test stimuli. The fact that even with such strong depth and slant cues the illusory figures were more deformed with increasing degrees of slant of the test stimuli rules out the possibility that the deformation is caused solely by the insufficiency of cues to depth and slant.

GENERAL DISCUSSION

We propose that this novel phenomenon of shape deformation of slanted illusory contours be termed depth release to denote the release of shape perception from the depth cues present in the inducing pattern. The term depth release contrasts with depth capture, a different type of phenomenon that can also be observed in the Ehrenstein grid. To induce depth capture, a textured screen is held above the Ehrenstein grid. The illusory patches are then seen lying in the plane of the overlying screen (Spillmann & Redies, 1981; Watanabe & Cavanagh, 1992). One explanation for this phenomenon is that depth signals in the illusory contours are relatively weak or easily overwhelmed by the much stronger depth cues provided by the superimposed screen (Watanabe & Cavanagh, 1992).

Although depth release and depth capture seem to be phenomena of opposite natures, they might occur for the same reason; i.e. the weakness or lack of depth signals in the illusory contours induced by the Ehrenstein grid. In Expt 2, all the subjects reported that the illusory figures themselves appeared to remain standing upright (0 deg) even when the rest of the test stimulus was clearly seen to be slanted. It has been reported that objects with weak depth cues appear to be at the same front-parallel depth plane (Gogel, 1965). Thus, the fact that the illusory figures constantly appeared to stand upright in the experiments may be due to weak depth signals in the illusory contours. Therefore, not only depth capture but also depth release might be explained by the relative weakness or lack of

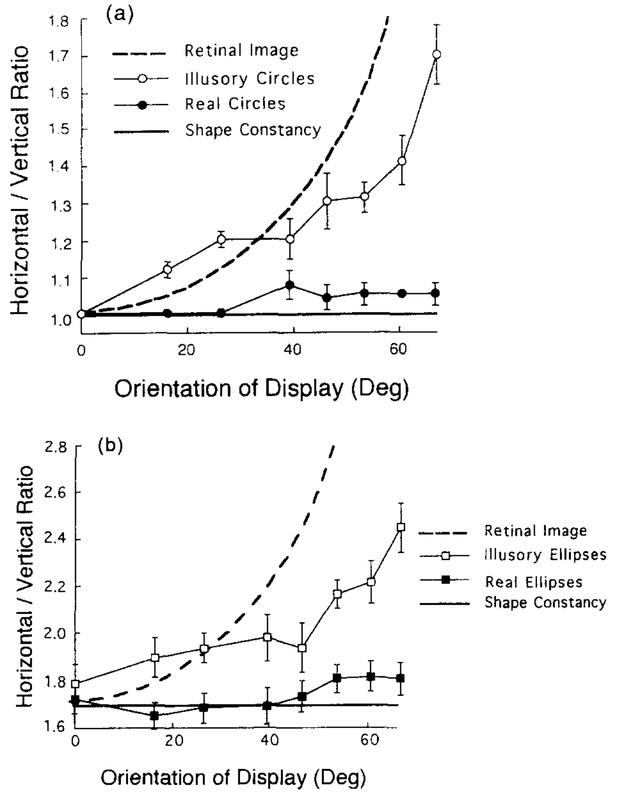

FIGURE 5. Results of Expt 2. The mean physical ratio of the horizontal/vertical radius of the ellipse (or the circle) of the reference figures the observers chose to match the shape of the presented test stimulus, plotted as a function of the degree of the tilt of the test stimulus. (a) Results for the illusory and real circles, (b) results for the illusory and real ellipses.

depth signals in illusory contours induced in the Ehrenstein grid.

Unlike the illusory contours induced by the line ends in the Ehrenstein grid, most other patterns inducing illusory surfaces do exhibit three-dimensional view stability (Carman & Welch, 1992), especially those induced by solid luminance edges. Analogous differential effects were found with depth capture. Illusory contours induced by the line ends produce depth capture, while illusory contours induced by solid luminance edges do not (Watanabe & Cavanagh, 1992). These differential effects may be caused by the difference between the strength of the depth signals in the illusory contours induced by line ends and those induced by solid luminance edges. Why does such difference in strength of depth signals occur? There are two possible explanations. One is that the difference in strength of the depth signals is caused by the difference in simple stimulus properties of the inducing figures. The binocular disparity between the vertical edges of the cut sectors in the solid or fine line patterns inducing illusory figures can determine the apparent depth of the illusory figures (Blomfield, 1973; Gregory & Harris, 1974; Ramachandran & Cavanagh, 1985). The vertical edges of the cut sectors in the solid inducing patterns would provide strong disparity signals (Rogers & Graham, 1983), whereas fine line patterns have only the fine end points of the horizontal lines which provide only weak disparity signals. The other possible explanation is that the difference in strength of the depth signals is determined by the difference in the strength of the binocular disparity signals that illusory contours themselves carry. The illusory contours induced by the solid edges provide strong binocular disparity signals, while the illusory contours induced by line ends do not. If true, this suggests that the illusory contours induced by line ends and by solid luminance edges are at least partially mediated by different mechanisms or processing levels. This view is in accordance with Grossberg and Mingolla's (1985) neural network model.

There are two assumptions concerning the purpose to which the visual system constructs illusory contours. One is that the construction of illusory contours serves to compensate for the loss of shape information normally provided by physically defined contours (e.g. Peterhans & von der Heydt, 1991; Ramachandran, 1990). When surface features such as luminance, color and texture of an object are similar to those of the background or adjacent objects, or when the physically defined contours are disturbed by irrelevant information such as cast shadows and highlights, the retinal receptors cannot detect the contours of the object in their entirety. To produce an internal reconstruction of the object, along with its contours, the visual system needs to interpolate the missing contours by constructing illusory contours as precisely as possible. The second assumption, which is not contradictory to the first, is that illusory contours or surfaces are constructed for the purpose of producing the internal representation of a visual stimulus that is most likely to occur in the real world* (e.g. Albert & Hoffman, 1995; Gregory, 1972). In this vein, the construction of illusory contours by the visual system serves the purpose of causing the observer to perceive the Ehrenstein grid as consisting of a complete grid with no gaps behind occluding figures, rather than as an incomplete set of lines that are accidentally collinear. According to the first assumption, the shape of illusory contours must be as similar to the shape of the real contours as possible. The present finding shows that the first assumption does not always hold true, for the shape of illusory figures in the Ehrenstein grid is variant over varying degrees of slant whereas the shape of the figures defined by real contours are much more invariant. The present finding does not contradict the second assumption; the illusory figures in the Ehrenstein grid appear to be perceived as occluding surfaces regardless of whether their shape changes with the degree of slant. Perhaps the primary purpose of

*However, the second assumption does not necessarily mean that illusory contours are generated in high-level cognitive processing as Gregory (1972) has suggested. There is a large amount of evidence that illusory contours are generated in low level processing by means of physiological methods (von der Heydt & Peterhans, 1989; Redies, Crook & Creutzfeldt, 1986) as well as psychophysical and computational methods (e.g. Banton & Levi, 1992; Dresp & Bonnet, 1991; Grossberg & Mingolla, 1985; Kellman & Shipley, 1991; Peterhans & von der Heydt, 1991; Shapley & Gordon, 1987; Watanabe & Oyama, 1988).

illusory contours induced by line ends is to serve to form the representation that is most likely to occur.

In conclusion, we found that illusory contours induced by the Ehrenstein grid have much less shape constancy than luminance defined contours.

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